

## APPLICATION OF REAL TIME INVERSE EDDY CURRENT ANALYSIS

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## INTRODUCTION

Rapid reduction of multifrequency eddy current data to direct material properties of conductivity and dimension has been a task for a number of years by Wallace et al. (1) and Seigfried (2,3). The direct solution of the electromagnetic boundary value problem and fitting data to experimental data can be accomplished but is slow and tedious(4,5,6). The direct solution approach has a slow cycle time and reduces both the spontaneous interaction of the operator to the test in progress and the resulting understanding of the process. The inverse approach of taking the raw eddy current data and producing physical data rapidly opens two possibilities for the measurement technique. In the area of process development and in difficult environments such as crystal growers, chemical reactors or heat treatment furnaces. It is possible to detect and stimulate transient events and isolate these reaction rapidly. Extending this application to automated operation one can use the resulting inverse data for control particularly in temperature measurement, where there is a conductivity dependence on temperature. For example in intrinsic semiconductors, copper and low carbon steels are currently important applications where traditional thermocouples or infrared gauging of temperature are not useful because of the difficult environments. For example where temperatures and thermal gradients are to be determined within a continuous product moving through a heat treatment furnace. More complex applications of inverse analysis is in determining reactions with bar surface due to diffusion and oxidation. Finally gauging for mean diameter and total volume of material is an area that is being explored with the next generation of experimental equipment that will have resolution of better

TABLE I

## Physical Requirements for Data Inversion

- 1) Minimum Three Frequencies or more if possible
- 2) Simultaneous Measurement
- 3) Absolute signal vector calibration
- 4) Noise threshold < .2%  
( transform stability requirement )
- 5) Frequency Selection spanning depths of interest
- 6) Characterized Standard

than 10 ppm. The key requirement for making measurements of conductivity and dimensioning are listed in Table I.

Data taking for inversion requires rather accurate data since the inverse transforms operates to generate a null results that is rather sensitive to proposed conductor structure. The multiple frequency inversion algorithm with good data will allow highly accurate determination of mean dimensions well beyond the accuracy of a single sample. This occurs because of the correlation of data within the inversion transform of the samples from the multiple frequencies.

The measurement system was designed around the operating requirement of the inversion transforms. This system is called the Datamac and it currently supports 4 simultaneous frequencies that typically operate from 10 Hz up to 5 Mhz. The calibration requirement were designed into the system so that standards which are not very close the unknown properties to be measured can be used. This is required because in semiconductors conductivities can easily vary over a range of an order of magnitude. In a simpler application of monitoring properties in the vicinity of the curie point in ferromagnetic material very large property changes can be detected.

#### General Discussion of the Inverse Transform

The inverse transform in cylindrical coordinates can be represented as a functional

$T[ \text{data} ; \text{proposed structure} ]$ .

Seigfried in his thesis gives the detailed an analytic representation as an integral transform(2) in cylindrical coordinates and Cartesian coordinates that could be characterized as:

$T[ f\{1\}, f\{2\}, \dots f\{n\} ; r\{1\}, \sigma\{1\}, r\{2\}, \sigma\{2\} \dots r\{m\}, \sigma\{m\} ]$

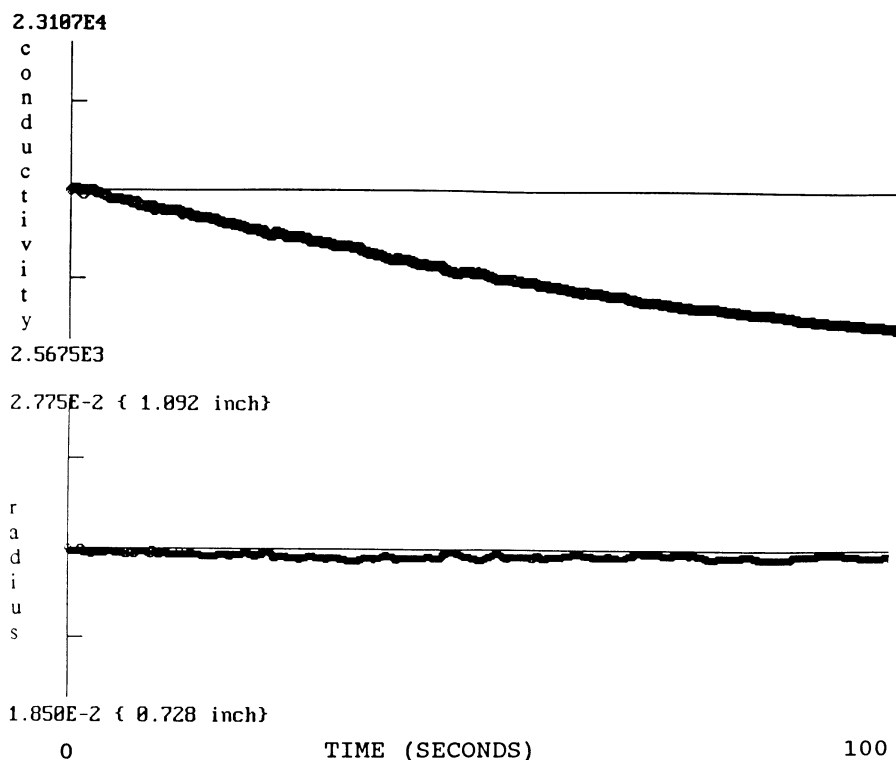


FIGURE 1 Exterior Inverse Analysis of a Cooling 50mm Dia. Silicon Crystal from 1100C to 600C over 100 Seconds. The Radial Conductivity in Mhos/m are shown Cooling. 19Khz, 43Khz, & 86Khz

Where  $f\{i\}$  represent frequencies,  $r\{i\}$  radial dimensions and  $\sigma\{i\}$  represent conductivities associated with a radial location. These integral are quite complex and form the core of a calculus of variation approach in using them as a sensitive detector of property changes. This integral is minimized by varying in the proposed structure in a self consistent fashion. In the bulk industrial applications requires speed and the most rapid calculation that can be performed is to determine the mean radius  $r\{1\}$  and the mean conductivity  $\sigma\{1\}$  iteratively to :

$$T[ f\{1\}, f\{2\}, f\{3\}, \dots f\{n\} ; r\{1\}, \sigma\{1\} ].$$

In our nomenclature we call this the exterior inverse analysis solution that produces the mean radius and conductivity. The interior inverse analysis produces an interior conductivity profile. An example of the exterior inverse analysis is shown for cooling silicon ingot whose temperature is being reduced from 1100C to 600C in Figure 1. Using three test frequencies on 16 Mhz 386/387 processor it takes approximately .3 seconds to produce this simplest of the inversions on a single sample for a cylindrical sample. One can note that the radial data has a higher degree of precision than the conductivity data. This difference in precision is due to the strong radial

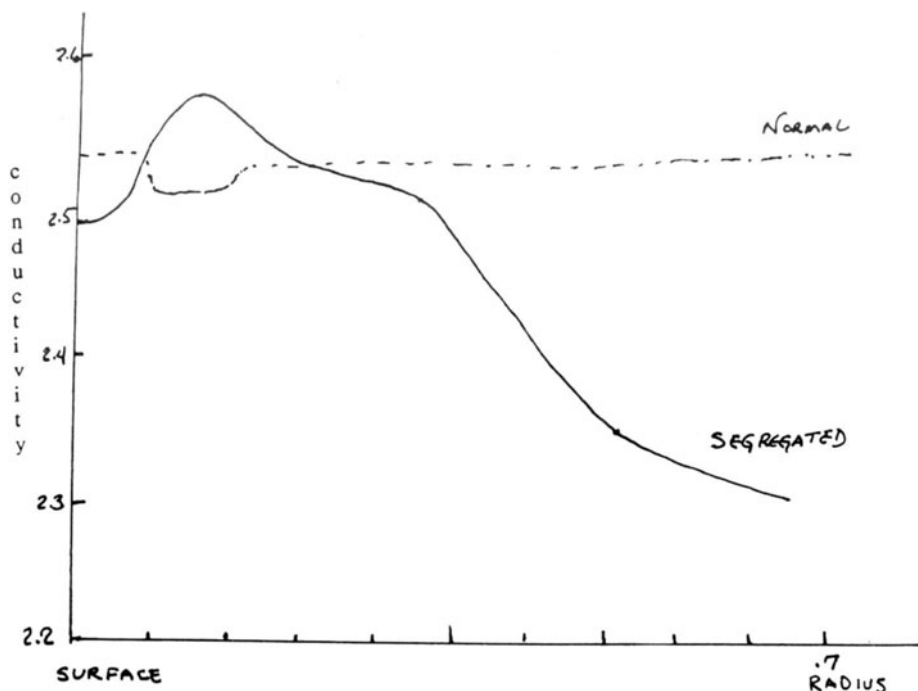


FIGURE 2 Interior Inverse Profile of Several Al 7%Si Ingots with One Ingot Showing Strong Segregation Measured at 300 Hz, 740 Hz, & 1000 Hz

dependence in the boundary condition that couples the field from the coil to the surface of the conductor. Currently for in service high temperature measurements the limiting accuracies are typically .1% for mean conductivity and .02% on the mean radius. The variation in the materials conductivity only appears within the propagation vector in the material whereas the external radius appears in a ratio multiplying the total response. This characteristic requires that very accurate data for useful conductivity data must be gathered. There is a limit to the number of frequencies that can simultaneously be used since there is a division of the total power by the number of frequencies in use which will reduce the final signal to noise ratio at each frequency. Frequency hopping rates are limited by the detection output band width which would limit this type of testing to static cases. For example in CZ crystal growth if melt studies are being performed interesting variations within the system can be up to 30 Hertz and these rates preclude the use of a frequency hopping systems.

Extending the inverse procedure to produce internal radial conductivity profiles can be performed as an extension to the inverse procedure already described. The values  $r\{1\}$  and  $\sigma\{1\}$  can be set or determined by the minimization procedure prior to determining internal conductivity profiles. For the long cylindrical geometry, we typically can select from the outer 20% to the outer 80% of the radius of the cylinder divided into 10 segments to

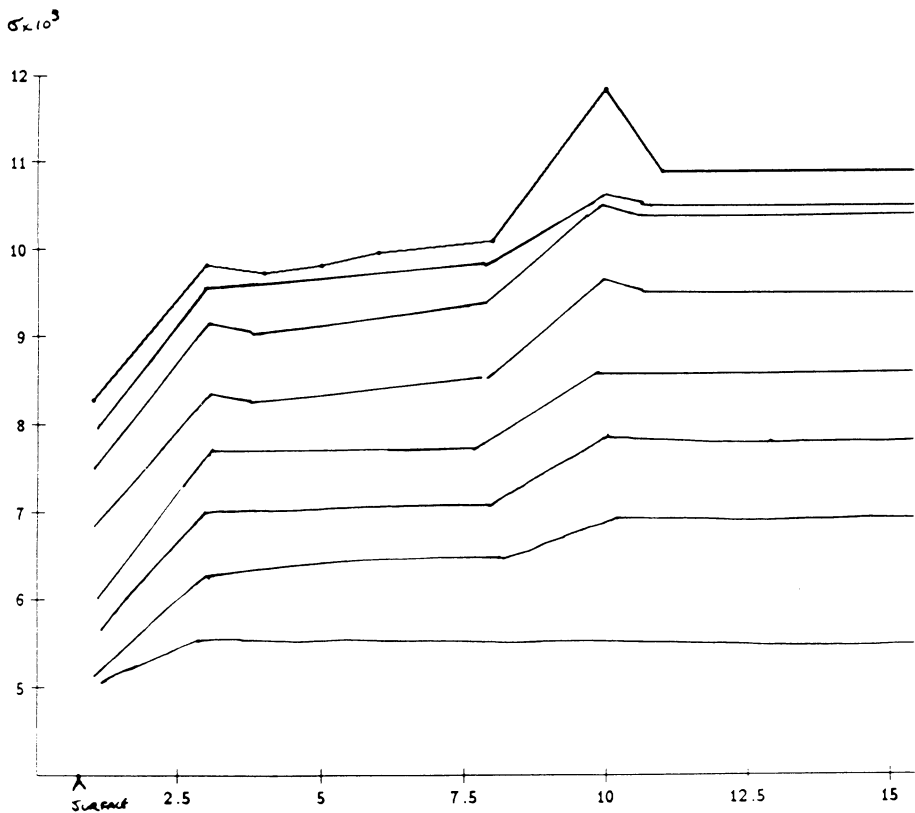


FIGURE 3 Sequence of Interior Inverse Analysis on the Cooling Silicon Ingot of Figure 1. This Shows the Development of the Thermal Gradient Within the Crystal at Selected Samples Along The Cooling Curve Over 100 Seconds.

determine the conductivity of each segment. The volume selected depends on the frequency set selected and the information desired. The internal profile of conductivity calculation if there is structure above a preset threshold can take up 100 times longer than finding the mean conductivity and radius by inversion. The exception to this case is if the material has a constant conductivity over the depth of interest and this is reported as rapidly as the mean radius and conductivity determination. Because of the increase in time requirement on continuous product multitasking processing for those sections showing changes in either  $r(1)$  or  $\sigma(1)$  are candidates for interior conductivity profiling. Typically this technique is used to detect segregation, environmental interaction with the surface, or cavities. If homogeneous standards are available then small conductivity variation as a function of depth can be isolated. In figure 2 is typical data on the conductivity variation in Al 7%Si casting alloy which is characteristic of dense and porous casting. In figure 3 are direct inversion for interior temperatures profiles from data that was produced on the same cooling silicon cylinder that was used in figure 1.

Gauging the diameter of cylindrical objects can be done quite accurately for the mean radius. However, only on total volume measurements is this particularly useful or in detecting surface reaction. The typical error can be seen on a 1" diameter brass bar of .0005" with a minimum of mechanical constraint in figure 4.

Figure 5 shows an exterior analysis on a step machined copper bar to determine the radii. This measurement was done at using three frequencies. A section was used as the standard radius and it was found that there was minimal or no variation between the measured and the determined value by the exterior inverse program. The variation or error increased or decreased significantly above or below the standard. For this data, the error is about .02%. This result indicates that this program can accurately be used to gauge the mean radius of product with slightly varying dimensions of material.

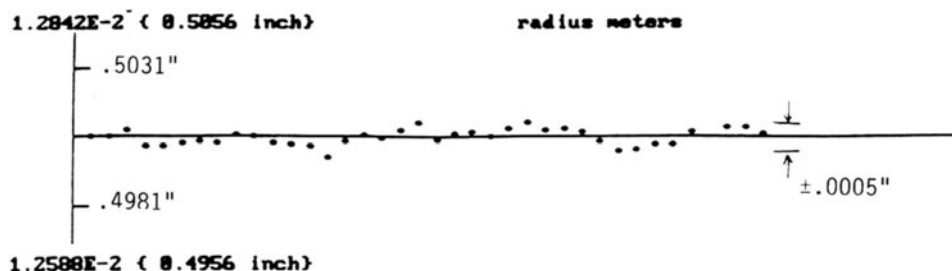


FIGURE 4 The Variation in Radius of a 1" diameter.  
Brass Bar Tested at 100 Hz, 250 Hz and 410 Hz  
in the Exterior Inverse Mode.

The major application of these techniques are currently in complex process development in difficult environments and heat treatment. We are currently extending our application programs to other test geometries and improving the degree of accuracy of our physical measurements.

#### ACKNOWLEDGEMENT

We would like to acknowledge the David Larkin of University of Texas and Junichi Kobayashi of Mitsubishi Metals for the data taken in Figure 1 and 3.

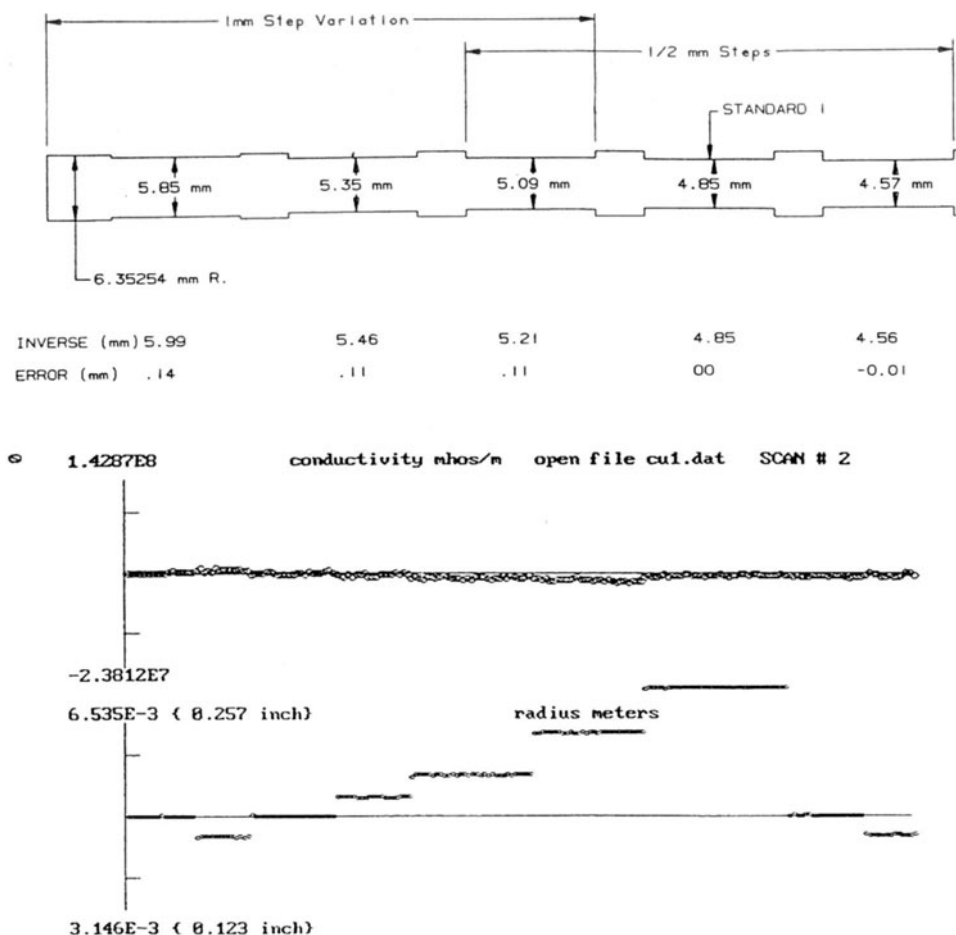


FIGURE 5 Copper Rod - Inverse Program. 1mm and 1/2 mm Step Radius with 1 inch gap between steps.

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